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How to Use Hand-Held Computers to Evaluate Wood Drying

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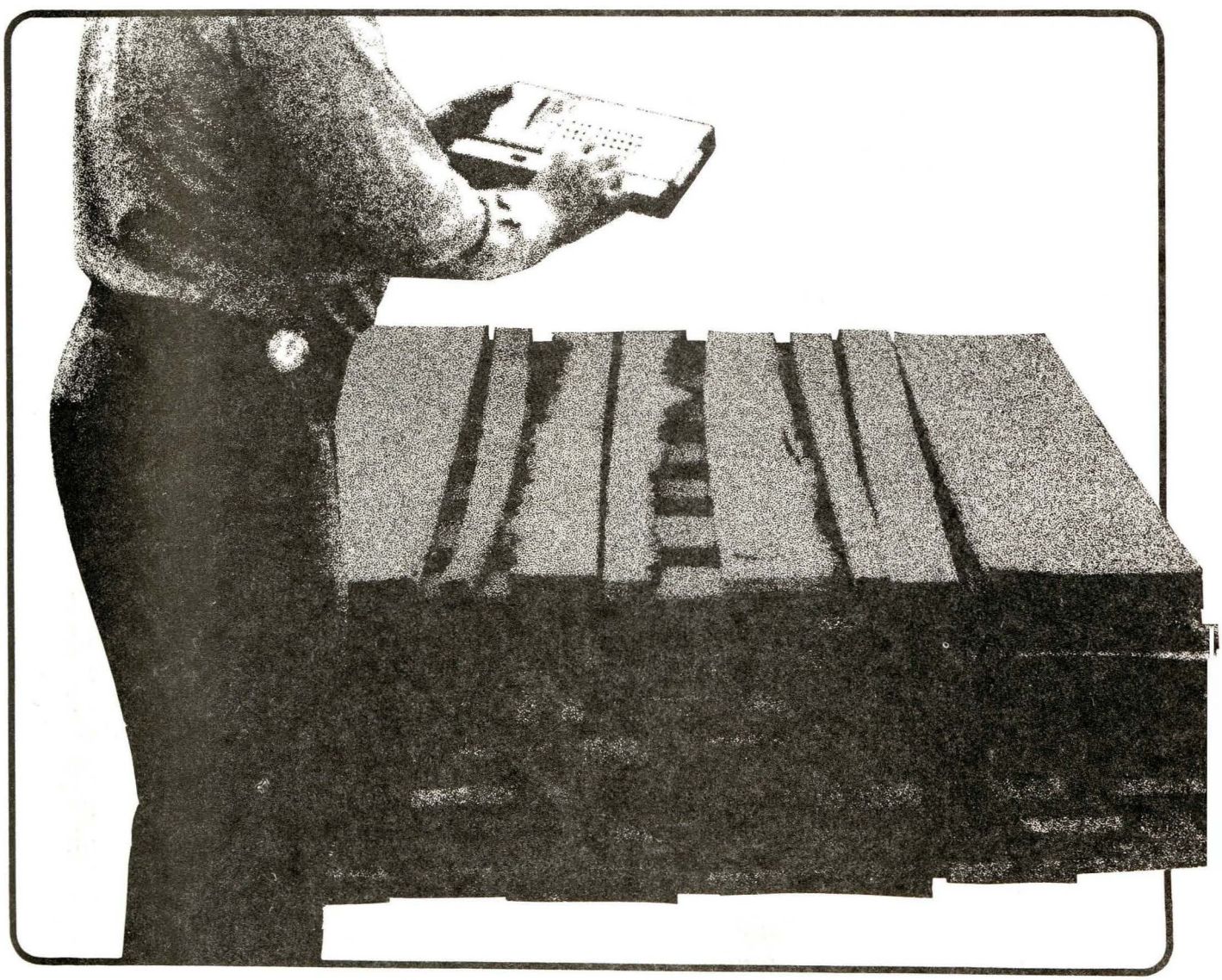

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HOW TO USE HAND-HELD COMPUTERS TO EVALUATE WOOD DRYING

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A gap exists between the theory and practice of industrial wood processing. Wood drying is one area where sophisticated theory and mathematical models have been developed and now need to be put into practice. Hand-held computers are one way of doing it. They have the advantage over larger models of being easily portable and inexpensive, yet they are capable of sophisticated programming.

Although several companies sell hand-held computers with 1 to 8K memory (Goldfarb and Griffin 1982), few programs have been available for the wood products industry. Drying is a time-consuming and expensive step in the processing of wood. Several mathematical models have been developed recently to assist drying operators in developing schedules, evaluating final drying times, and determining basic properties of wood exposed to a particular drying environment. This paper describes several basic drying programs developed for a hand-held computer.

PROGRAMS

Five separate programs written in BASIC have been developed for a Sharp[1] PC 1500 pocket computer (weighing less than 1 lb) with a 3.5K random access memory (RAM). These programs are combined into a program package called DRYPAC (see tabulation below):

Programs Developed in DRYPAC

EMC	Determines equilibrium moisture content, humidity, or wet-bulb temperature from basic psychrometric relationships.
FIT-CURVE	Determines parameters a and b by fitting Equations (18) and (19) to a data set of three points.
FIT-CURVE-A	Determines approximate a and b when FIT-CURVE does not converge.
DRY-CURVE-1	Determines and plots a drying curve and tabulates moisture content versus time for ten time increments.
DRY-CURVE-2	Determines and plots relative moisture content versus time; tabulates these values as well as relative drying rates for ten time increments.

Programs are stored on audio cassette tapes and fed into the computer from a tape recorder. Once inside the computer memory, the program is initiated by pressing the RUN button. Only one of the five programs can occupy RAM at a given time.

Output appears on a dot graphic liquid crystal display area directly on the computer or on a four-color X-Y plotting Sharp CE-150 printer which is a separate unit. The computer, interface, and printer weight less than 3 lbs and are easily carried to any part of the wood processing plant (fig. 1).

The programs can be used on any small computer using the BASIC programming language having 3.5K RAM, but generally would have to be modified for input/output format and plotting commands. Most hand-held computers such as the Radio Shack TRS80 PC-2 or the Panasonic HHC could take a modified program.

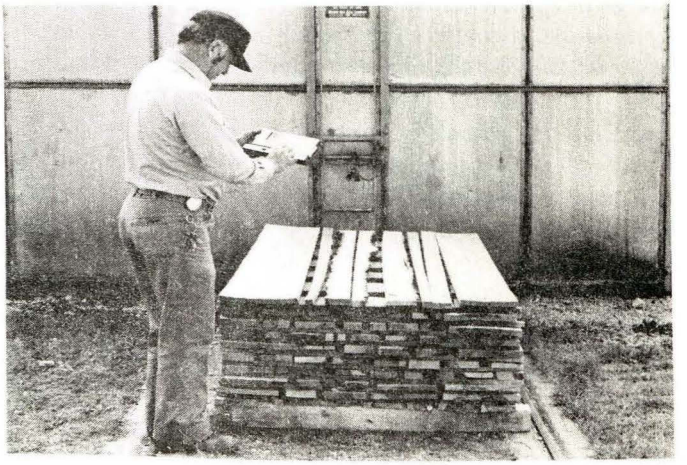

Figure 1.--*Hand-held computers can be easily carried to perform complex calculations in any part of the processing plant.*

[1]*Use of trade names does not constitute endorsement of the products by the USDA Forest Service.*

Program EMC

To evaluate a drying curve, equilibrium moisture content, EMC, must be determined from the conditions in the kiln. The EMC at atmospheric pressure is a function of dry-bulb temperature and either relative humidity or wet-bulb temperature. Also, Program EMC provides the user with EMC over a range of dry-bulb temperatures from 32 to 400°F, which is more extensive than most published tables. Program EMC calculates enthalpy and either relative humidity (RH), if wet-bulb temperature (TWB) is given, or TWB, if RH is given (fig. 1a and list 1a in Appendix B). Humidity calculations are made from basic psychometric relationships (Appendix A) (Elliott 1983).

The program will ask for dry-bulb temperature ("TDB = ?") and relative humidity "RH = ?"). If RH is not known, any negative number can be input, i.e. "−1," and the program will ask for wet-bulb temperature ("TWB = ?"). Temperatures should be input to 0.1°F and RH to 0.1 percent. The program requires less than 3 minutes to run in most situations.

Output illustrated by three separate outputs (table 1), will include the input data as well as either RH or TWB, EMC to 0.1 percent, and enthalpy to 0.1 Btu/lb dry air. If an improper RH is input to the program, the message "INVALID HUMIDITY" will be the output.

Program FIT-CURVE

If data of moisture content at various drying times are given, Program FIT-CURVE will determine two parameters, a and b (will list as A and B for clarity of copy), which describe and can be used to calculate basic properties of the curve (fig. 2a and list 2a in Appendix B). Moisture content data (initial moisture content, equilibrium moisture content, and moisture content at three selected times) must be entered into the program. The three moisture contents at selected times must be converted to relative moisture content, E, by Equation (12) and then must meet the following criteria: one at a short time (E_S, t_S) where $E > 0.90$, one when approximately half the water is removed from the wood (E_M, t_M) where $0.45 < E < 0.55$, and

Table 1.--*Sample outputs from Program EMC*

1		2		3	
GIVEN:		GIVEN:		GIVEN:	
TDB =	140.0	TDB =	215.0	TDB =	300.0
TWB =	110.0	TWB =	205.0	RH =	21.9
RESULTS:		RESULTS:		RESULTS:	
RH =	38.8	RH =	81.8	TWB =	211.5
EMC =	5.8	EMC =	10.3	EMC =	0.8
ENTHALPY =	91.3	ENTHALPY =	4754.1	ENTHALPY =	99830.2

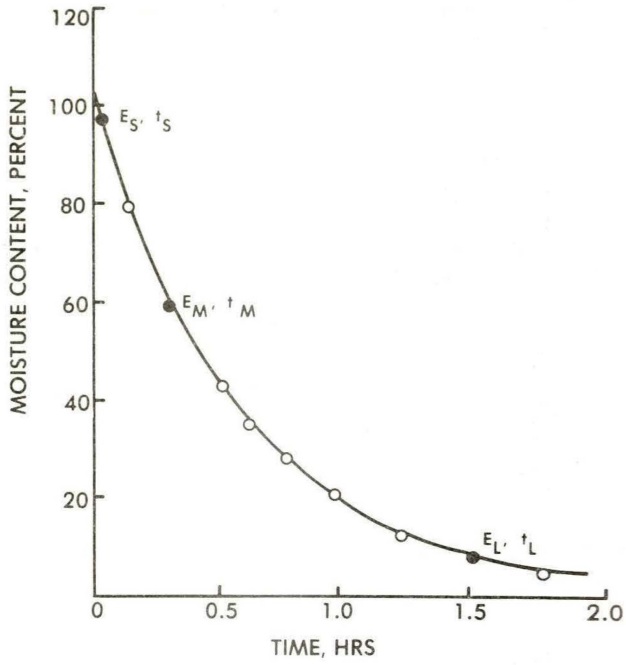

Figure 2.--*Typical drying curve and three data points required for input to Program FIT-CURVE (see Input 1 in table 2).*

one at a long time (E_L, t_L) where $E < 0.15$ (fig. 2). Also, the range of time data should be in units such that the maximum time is no greater than 100, but optimally near 10. For example, if E = 0.04 at 3000 minutes, the program will run more efficiently if the minutes were converted to 50 hours.

The program will ask for initial moisture content ("IMC ="), equilibrium moisture content ("EMC ="), and data points ("TS =", "MCS =", "TM =", "MCM =", "TL =", "MCL ="). Moisture contents should be input to 0.1 percent and times to three decimal places or less. Output consists of values for A, B, and D (criterion for fit; $D < 0.01$ is a good fit).

Sample input of data show convergence of a and b in 4 minutes with a very close fit (table 2--Input and Output 1). In many cases for highly nonlinear functions, the program will not converge. Thus, a message "TRY ALTERNATE" will be output after approximately 10 minutes as in table 2--Input and Output 2. A solution with the data of Input 2 can be approximated with Program FIT-CURVE-A.

Program FIT-CURVE-A

If the Program FIT-CURVE does not converge to value of a and b, this program will provide values (fig. 3a and list 3a in Appendix B). The program requires the same input format and will provide the same output format (except that the criterion for fit is DA rather than D) as Program FIT-CURVE. The Pro-

Table 2.--*Sample Input and Output from Program FIT-CURVE and FIT-CURVE-A*

FIT-CURVE

Input 1

"IMC ="	105.0,	"EMC ="	5.0	"IMC ="	74.0,	"EMC ="	4.0
"TS ="	0.04,	"MCS ="	97.3	"TS ="	0.004,	"MCS ="	70.5
"TM ="	0.30,	"MCM ="	59.0	"TM ="	0.50,	"MCM ="	43.2
"TL ="	1.50,	"MCL ="	8.5	"TL ="	4.50,	"MCL ="	8.9

Input 2

Output 1

"A = 2.036"
"B = 0.914"
"D = 0.002"

Output 2

"TRY ALTERNATE"

FIT-CURVE-A

Input 3
(Same as Input 2)

Output 3

"A = 4.151"
"B = 3.850"
"DA = 0.049"

gram FIT-CURVE-A will not give as close a fit as FIT-CURVE and requires 10 minutes computing time but is adequate in many instances (table 2--Input and Output 3).

Program DRY-CURVE-1

This program generates a drying curve of moisture content versus time (fig. 4a and list 4a in Appendix B). The program will ask for parameter values ("A = ?", "B = ?"), initial and equilibrium moisture contents ("IMC = ?", "EMC = ?") and units of time ("TIME UNITS = ?"). Units of time must fill four spaces, such as DAYS, HRS., MIN., SEC., etc. Output consists of a drying curve in moisture content (MC) in percent versus time (T), a table of the same information with data to two decimal places, and a listing of A, B, and EMC (fig. 3). The program provides results in 3 to 5 minutes depending on the values of the parameters.

Program DRY-CURVE-2

This program is similar to DRY-CURVE-1, only the program is intended for more basic work (fig. 5a and list 5a in Appendix B). Input requires only parameter values ("A = ?", "B = ?"). Output provides a plot of relative moisture content, E versus drying time, a table of dry time (T), E, and relative drying rate (RDR) in scientific rotation to three significant digits calculated from Equation (13) (fig. 4). Researchers should find this program useful to determine initial drying rates and characteristic drying curves.

General

DRYPAC is most applicable when drying is being done at constant conditions of temperature and humidity, so that EMC is constant during the entire drying time. Constant conditions are not normally maintained in commercial drying operations. In many cases, drying curves for varying conditions can be fit with the analysis of DRYPAC by assuming EMC is equal to that at the final drying conditions.

SUMMARY AND OUTLOOK

The program package DRYPAC can be helpful to wood processors and researchers in fitting drying data, predicting drying times, and evaluating basic parameters for efficient kiln operation. The programs are readily adaptable to hand-held computers and can be saved on cassette tape.

The development of DRYPAC allows for expansion and alteration as computer technology advances. Two possible programs to add are an economic analysis program and a program to predict drying times based on wood characteristics and kiln conditions. Microcomputer hardware technology is progressing at such a rapid pace that details of the programs might be

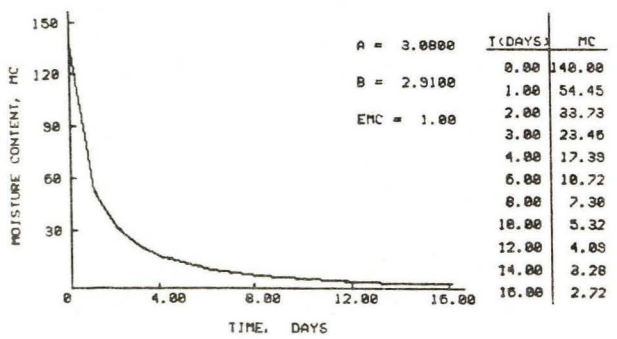

Figure 3.--*Example output of moisture content versus time plot and tabular values from Program DRY-CURVE-1.*

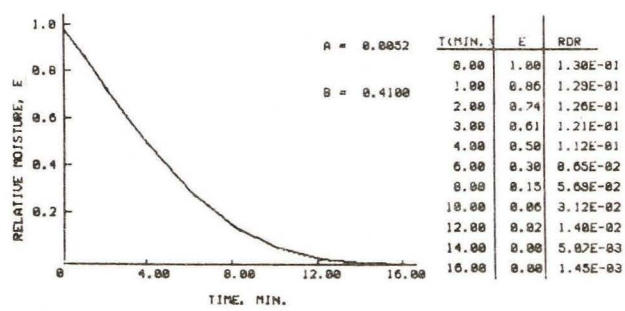

Figure 4.--*Example output of relative moisture content versus time plot and tabular values from Program DRY-CURVE-2.*

done more efficiently in the near future. For example, hand-held computers now have 16K RAM plug-in units which could store the entire DRYPAC package. The wood industry must be alert to the expanding microcomputer technology and use this technology to produce the best quality wood product in the most efficient manner.

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APPENDIX A

a	rate factor, hr^b
b	bend factor
D	difference defined by Eq. (22)
DA	difference defined by Eq. (23)
E	relative moisture content
$\dot{E}$	drying rate, hr^{-1}
h	relative vapor pressure
H	enthalpy, Btu/lb dry air
p	vapor pressure of water, psi
RH	relative humidity, percent
t	time, hr
T	temperature, °F
X	moisture content, lb water/lb dry wood
Y	absolute humidity, lb water/lb dry air
α's	constants in Eq. (2)
Γ(b)	gamma function, $\Gamma(b) = \int_0^\infty s^{b-1} \exp(-s)ds$
σ	parameter defined by Eq. (17)

Subscripts

db	dry bulb
e	equilibrium
f	final
i	initial
L	long time
M	middle time
s	saturation
S	short time
wb	wet bulb

THEORY

Program EMC

The equilibrium moisture content, X_e, must be determined from relative humidity, RH, and dry-bulb temperature, T_{db} (Simpson and Rosen 1981)

$$h = 0.01\ RH \tag{1}$$

$$X_e = \left[\frac{\alpha_1\alpha_2 h}{1 + \alpha_1\alpha_2 h} + \frac{\alpha_2 h}{1 - \alpha_2 h}\right]\frac{1800}{\alpha_3} \tag{2}$$

where:

$\alpha_1 = 3.730 + 0.03642T_{db} - 0.000154T_{db}^2$
$\alpha_2 = 0.6740 + 0.001053T_{db} - 0.000001714T_{db}^2$
$\alpha_3 = 216.9 + 0.01961T_{db} + 0.005720T_{db}^2$

Relative humidity can be determined from wet- and dry-bulb temperatures using the following psychrometric relationships (Elliot 1983):

$$Y = \frac{(1093 - 0.556T_{wb})Y_{s,wb} - 0.240(T_{db} - T_{wb})}{1093 + 0.444T_{db} - T_{wb}} \tag{3}$$

Also,

$$Y_s = \frac{0.622\ p_s}{14.7 - p_s} \tag{4}$$

$p_s = 0.000145 \exp[-5800/T' + 1.391 - 0.04864\ T' + 0.4176 \times 10^{-4}\ T'^2 - 0.1445 \times 10^{-7}\ T'^3 + 6.546\ \ln(T')]$ (5) is the saturation vapor pressure of water

and

$T' = \frac{T + 459.6}{1.8}$ is a conversion factor. (6)

Absolute humidity can then be determined by evaluating Equations (4) and (5) at the wet-bulb temperature and plugging in the value of $Y_{s,wb}$ into Equation

(3). Further

$$p = \frac{14.7Y}{0.622 + Y} \quad (7)$$

Knowing p, $p_{s,db}$ can be evaluated from Equation (5) to obtain:

$$RH = 100(p/p_{s,db}) \quad (8)$$

Enthalpy, H, in Btu/lb dry air can be evaluated from the following relationship:

$$H = 0.240(1 + 8.33 \times 10^{-6}T_{db})T_{db} + Y[1061 + 0.444(1 + 4.464 \times 10^{-6} T_{db})T_{db}] \quad (9)$$

The program is straightforward when T_{db} and T_{wb} are given. Equation (3) is evaluated for absolute humidity, Y, which can then be substituted into Equation (7) to determine the vapor pressure of water in the humid air. The saturation vapor pressure of water at the dry-bulb temperature, $p_{s,db}$, can be obtained from Equation (5) and, thus, relative humidity calculated from Equation (8).

When RH is given, a programmed iterative Newton method solves Equation (3) for T_{wb}. The mathematics are similar to the solution when T_{wb} is given. In this case, $Y_{s,wb}$ in Equation (3) is a complex function of T_{wb} and is unknown. Thus, a numerical technique is required to solve for T_{wb}. This iterative procedure becomes unstable near a T_{wb} of 212°F; thus, several safeguards are placed in the program to ensure a reasonable value of T_{wb} as T_{wb} approaches 212°F. If T_{wb} is determined to be greater than 211.5°F, the value is set at 211.5°F for calculations of enthalpy. For most practical kiln operations, conditions will not go above 211.5°F T_{wb}. The program also ensures that a proper RH is input; e.g. that RH cannot go above 22 percent at 300°F T_{db} and atmospheric pressure. Enthalpy is calculated from Equation (9).

Program FIT-CURVE

Drying curves for wood products are defined in terms of a rate factor, a, and bend factor, b (Rosen 1980, 1982):

Drying curve

$$E = 1 - \dot{E}_i \int_0^t \exp(-a\tilde{t}^{1/b})d\tilde{t} \quad (10)$$

where

$$\dot{E}_i = \frac{a^b}{b\Gamma(b)} \quad (11)$$

$$E = \frac{X - X_e}{X_i - X_e} \quad (12)$$

Relitive drying rate

$$-\frac{dE}{dt} = \dot{E} = \dot{E}_i \exp(-at^{1/b}) \quad (13)$$

The series solution to Equation (10) is:

$$E = 1 - \dot{E}_i t \sum_{n=0}^{\infty} \frac{(-1)^n a^n t^{n/b}}{(n/b + 1)n!} \quad (14)$$

An approximate solution to Equation (10) is:

$$E = 1 - \frac{\sigma^b}{b\Gamma(b)}\left(1 - \frac{b\sigma}{b + 1}\right); \ \sigma \leq 0.5 \quad \text{(short times)} \quad (15)$$

$$E = \frac{\sigma^{b-2}\exp(-\sigma)(\sigma + b - 1)}{\Gamma(b)}; \ \sigma \geq 2.0 \quad \text{(long times)} \quad (16)$$

where

$$\sigma = at^{1/b} \quad (17)$$

The program substitutes input values of E_S, t_S and E_L, t_L into Equations (15) and (16).

$$E_S = 1 - \frac{a^b t_s}{b\Gamma(b)}\left(1 - \frac{bat_S^{1/b}}{b + 1}\right) \quad (18)$$

$$E_L = (at_L^{1/b})^{b-2} \exp(-at_L^{1/b})(at_L^{1/b} + b - 1)/\Gamma(b) \quad (19)$$

Equations (18) and (19) are solved for a and b by a two-dimensional Newton-Raphson Method (Stark 1970). The gamma function of b is solved by a series expansion (Davis 1963).

Initial values of a and b must be carefully selected because of instabilities in the Newton-Raphson Method with these highly nonlinear functions. Also, Equations (18) and (19) can converge to two sets of answers depending on the initial guess of a and b--one set with $b < 1.0$ and one set with $b \geq 1.0$. Techniques have been developed to generate good initial guesses for a and b and to have a method for picking the best final values for a given set of data.

The value of b is the most critical since this value determines the degree of nonlinearity of Equation (10). From past experience (Rosen 1982), values of b fall in the range of 0.2 to 4.0. Thus, the numerical solution uses a stepwise searching technique starting with a value of b = 0.15 and incrementing b by selected amounts until a solution is found or until b = 4.0. Once each b is given, a is estimated from Equation (11):

$$\dot{E}_i = \text{initial slope of drying curve} = \frac{1.0 - E_S}{t_S} \quad (20)$$

$$a = [(\frac{1.0 - E_S}{t_S})b\Gamma(b)]^{1/b} \quad (21)$$

When two solutions are found for Equations (18) and (19), a comparision is made to determine the best solution of the two. Values of E_M and t_M from the data and those calculated by Equation (14) are substituted into the following equation:

$$D = \sqrt{(\Delta E_M^2 + 2\Delta E_L^2)/3} \quad (22)$$

where $\Delta E_M = E_M$ (calculated) $- E_M$ (data)
$\Delta E_L = E_L$ (calculated) $- E_L$ (data)

Equation (22) gives added numerical emphasis to the end of the drying, where small absolute differences in E can make a bigger difference in t than in earlier drying stages. The values of a and b corresponding to the lowest value of D are the optimal values.

Program FIT-CURVE-A

The program is similar to FIT-CURVE, but uses a direct calculation rather than the Newton-Raphson Method. The function DA is minimized over a range of b's from 0.05 to 4.1; where this range is divided into 24 increments of increasing size as the value of b increases. Greater numerical emphases on Δ E's are given on the middle and end of drying.

$$DA = \sqrt{(0.5\ \Delta E_S^2 + \Delta E_M^2 + 2\Delta E_L^2)/3.5} \quad (23)$$

where $\Delta E_S = E_S$ (calculated) $- E_S$ (data)

Program DRY CURVE-1

The program uses values of a, b, X_i, and X_e to generate a drying curve. The program must first estimate the final time to dry slightly above X_e so that the time axis of the graph can be determined.

$$t_f = (\frac{1.5 + 2b}{a})^b \quad (24)$$

Final time is then divided into ten increments, such that the four increments are closer together than the remaining six. E's are calculated for each t by Equation (14) and transformed to moisture content by Equation (12).

Program DRY-CURVE-2

Only drying parameters a and b need to generate the drying curve of E versus t by Equation (14).

Relative drying rates, $\dot{E}$, are also calculated at each t by Equation (13).

APPENDIX B — LOGIC DIAGRAMS AND LISTING OF PROGRAMS IN DRYPAC

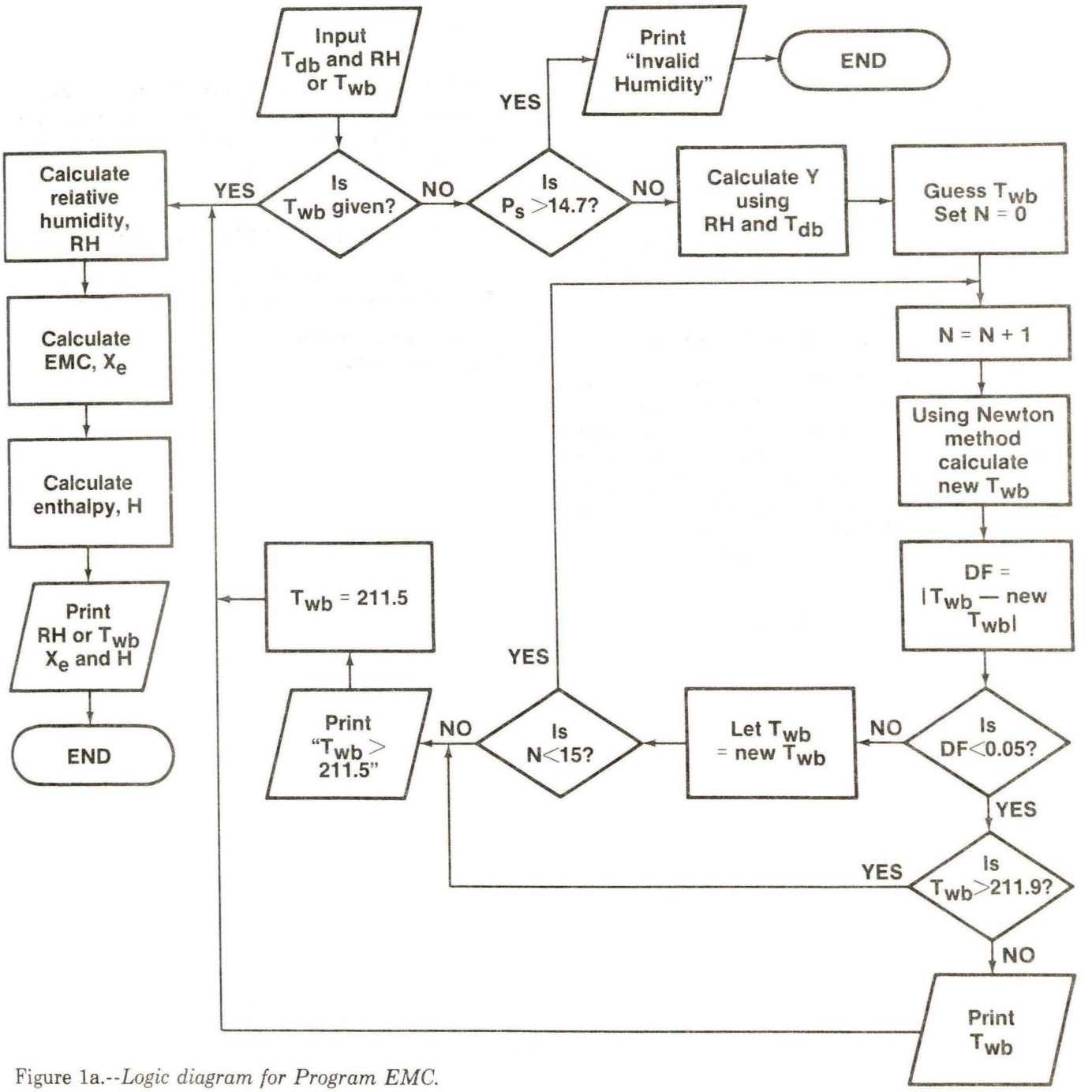

Figure 1a.--*Logic diagram for Program EMC.*

```
  6:COLOR 0:INPUT "TDB=?";TD:INPUT "RH=?";RH
 25:TW=0:R1=RH:IF RH>0GOTO 30
 27:INPUT "TWB=?";TW
 30:LPRINT "   GIVEN:            "
 31:COLOR 1:LPRINT USING "##########.#";"TDB =";TDB
 32:IF RH>=0LPRINT "RH = ";RH
 33:IF RH<0LPRINT "TWB =";TW
 34:LPRINT " "
 35:COLOR 0:LPRINT "   RESULTS:"
 36:COLOR 3:LPRINT " "
 40:T=TD:GOSUB 600
 41:PD=PS
 45:N=0:IF RH>0GOTO 250
 50:T=TW
 55:GOSUB 600
 60:PW=PS:YS=Y2:Y=Y3
 72:IF Y<0LET Y=0
 75:P=(14.7*Y)/(.622+Y):IF N>0GOTO 90
 80:RH=P/PD*100
 85:LPRINT "RH = ";RH
 90:K1=3.73+.03642*TD-.0001547*TD*TD
 95:K2=.674+.001053*TD-.000001714*TD*TD
100:W=216.9+.01961*TD+.00572*TD*TD
105:H1=RH/100
110:EM=((K1*K2*H1)/(1+K1*K2*H1)+K2*H1/(1-K2*H1))*1800/W
115:LPRINT "EMC =";EM
120:HA=.24*(1+8.33E-6*TD)*TD
125:HB=Y*(1061+.444*(1+4.464E-6*TD)*TD)
130:H=HA+HB
135:LPRINT USING "#######.#";"ENTHALPY=";H
190:END
250:P=RH*PD/100
255:Y=(P*0.622)/(14.7-P)
280:TA=TD-20
285:T=TA:GOSUB 600
286:N=N+1
290:P1=PS:F1=Y-Y3
300:TB=TA-.005
305:T=TB:GOSUB 600
310:P0=PS:F0=Y-Y3
360:DR=(F1-F0)/.005
365:TW=TA-(F1/(DR))
367:IF TW<212GOTO 375
368:TA=211
373:GOTO 395
375:DF=ABS (TW-TA)
385:IF DF<.05GOTO 450
390:TA=TW
395:IF N=15GOTO 500
400:GOTO 285
450:LPRINT "TWB =";TW
460:GOTO 50
500:LPRINT "TWB >         211.5"
510:TW=212:GOTO 50
600:T1=T:T=(T+459.6)/1.8
610:PS=EXP (-5800/T+1.391-0.04864*T+0.4176E-4*T*T-.1445E
    -7*(T^3)+6.546*LN T)
620:PS=PS*0.000145
625:IF T1=TDGOTO 670
627:IF PS>14.69GOTO 368
630:Y2=(.622*PS)/(14.7-PS)
635:Y3=((1093-.556*T1)*Y2-.240*(TD-T1))/(1093+.444*TD-T1)
670:RETURN
```

List 1a.--*Program for EMC.*

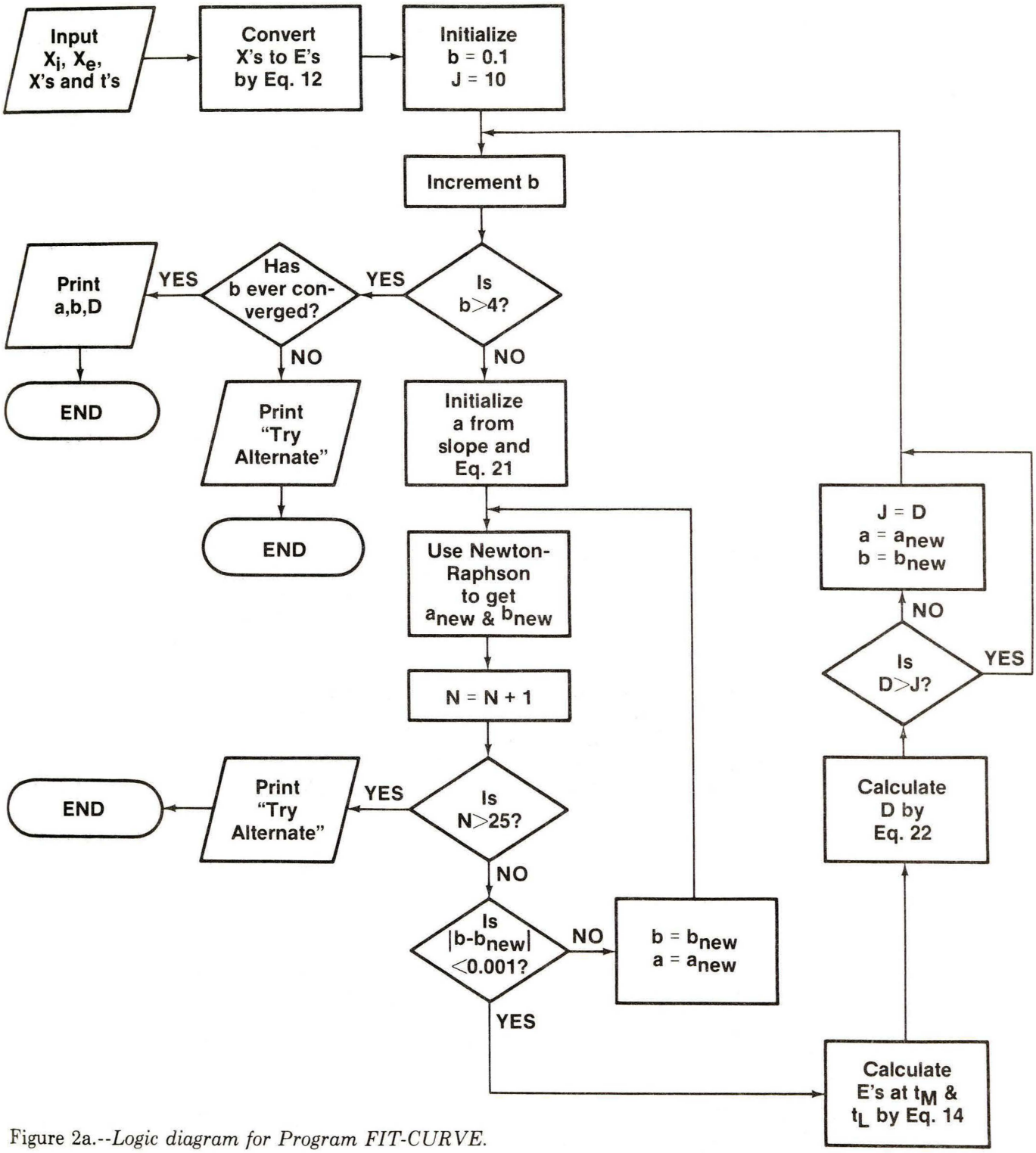

Figure 2a.--*Logic diagram for Program FIT-CURVE.*

```
  5:INPUT "IMC=";J:INPUT "EMC=";B:A=J-B
 10:INPUT "TS=";T1:INPUT "MCS=";E1:INPUT "TM=";T2:E1=(E1-B)/A
 11:INPUT "MCM=";E2:E2=(E2-B)/A:INPUT "TL=";T3:INPUT "MCL=";E3:
    B2=.1:E3=(E3-B)/A:J=10
 17:B2=B2+.05:N=0:COLOR 0
 18:IF B2>.5LET B2=B2+.10
 19:IF B2>1.2LET B2=B2+.4
 21:B=B2:GOSUB 600
 22:A=((1-E1)/(T1)*B*G)^(1/B):IF B2>4GOTO 269
 25:B0=B:G0=G:A0=A
 27:B1=B0+.005:A1=A0+.005:B=B1:GOSUB 600
 55:G1=G:A=A0:B=B0:G=G0:GOSUB 500
 70:FA=D:A=A1:B=B0:G=G0:FB=M:GOSUB 500
 85:FC=D:A=A0:B=B1:G=G1:FE=M:GOSUB 500
100:G=(FC-FA)/.005:R=(D-FA)/.005
115:EZ=(FE-FB)/.005:FZ=(M-FB)/.005
125:X=G*FZ-EZ*R:N=N+1:IF X=0GOTO 17
130:A1=(G*A0+R*B0-FA)*(FZ/X)-(EX*A0+FZ*B0-FB)*(R/X)
131:IF A1<0.005GOTO 17
140:B1=-(G*A0+R*B0-FA)*(EZ/X)+(EZ*A0+FZ*B0-FB)*(G/X)
141:IF B1<.01GOTO 17
142:IF B1>14GOTO 17
143:IF N>25GOTO 280
145:A0=ABS (B1-B0):B=B1:A=A1:GOSUB 600
155:IF A0>.001THEN GOTO 25
215:EZ=(A^B)/(B*G):T=T2:GOSUB 700:FZ=(E-E2)^2
230:T=T3:GOSUB 700:D=((FZ+2*(E-E3)^2)/3)^(0.5):IF D>JGOTO 17
255:J=D:B3=B:A3=A:IF B2>3GOTO 270
259:IF B2<1LET B2=1:GOTO 17
269:IF A3=0GOTO 280
270:LPRINT USING "###.###";"A =";A3:LPRINT "B =";B3:LPRINT " ":
    COLOR 3:LPRINT "D =";J:END
280:LPRINT "TRY ALTERNATE":END
500:D=((A*T3^(1/B))^(B-B2))*(EXP (-A*T3^(1/B)))*((A*T3^(1/B)
    +B-1)/G)-E3
555:M=1-E1-(T1*A^B)/(B*G)+(A^(B+1)*T1^((B+1)/B))/(B*G+G):RETURN
600:M=1:X=B
625:IF B<=1GOTO 645
630:M=M*(B-1):B=B-1:GOTO 625
645:G=B+.5772156*(B^2)+(-.655878)*(B^3)+(-.042003)*(B^4)+
    (.1665386)*(B^5)
650:D=(-.0421977)*(B^6)+(-.009622)*(B^7)+(.007219)*(B^8)+
    (-.001165)*(B^9)
655:G=M/(G+D+(-.0002152)*(B^10)):B=X:RETURN
700:X=0:G=0:N=0:R=1
705:GOTO 765
710:N=N+1:R=R*N
765:X=X+(-1)^N*A^N*T^(N/B)/(N/B+1)/R:D=ABS (X-G)
780:IF  D<0.000001GOTO 790
782:G=X:GOTO 710
790:E=1-(EZ*T*X):RETURN
```

List 2a.--*Program for FIT-CURVE.*

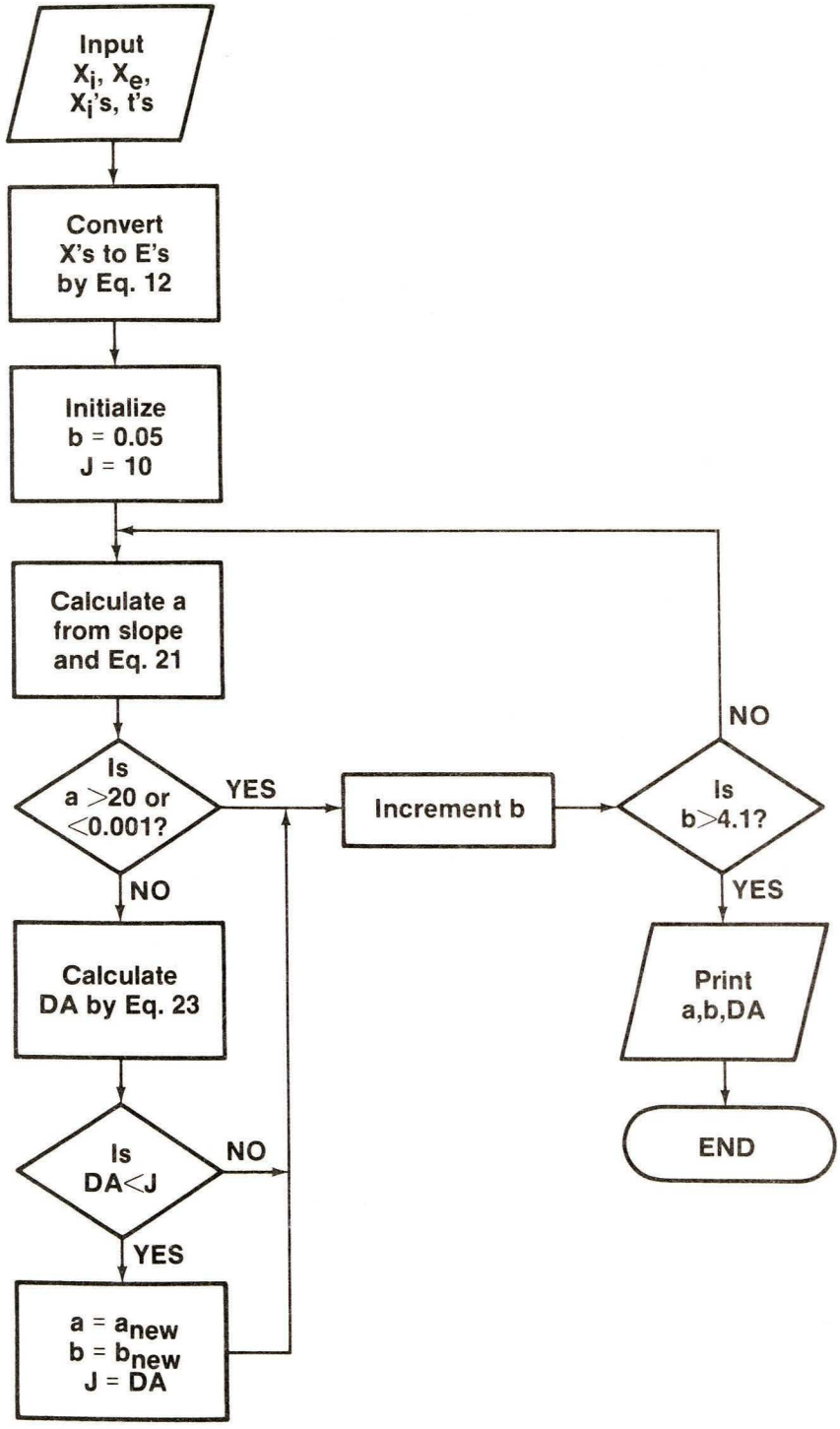

Figure 3a.--*Logic diagram for Program FIT-CURVE-A.*

```
  5:INPUT "IMC=";J:INPUT "EMC=";B:A=J-B
 12:INPUT "TS=";T1:INPUT "MCS=";E1:E1=(E1-B)/A
 13:INPUT "TM=";T2:INPUT "MCM=";E2:E2=(E2-B)/A
 15:INPUT "TL=";T3:INPUT "MCL=";E3:E3=(E3-B)/A
 17:J=10:CSIZE 2
 19:B=0.05
 21:GOSUB 600
 22:A=(B*G*(1-E1)/(T1))^(1/B)
 23:IF A>20GOTO 300
 24:IF A<.001GOTO 300
100:H=(A^B)/(B*G):T=T1:GOSUB 700
105:D1=((E1-E)^2)*.5:T=T2:GOSUB 700
115:D2=(E2-E)^2:T=T3:GOSUB 700
120:D3=((E3-E)^2)*2
125:DF=((D1+D2+D3)/3.5) 0.5
200:IF DF>JGOTO 300
210:J=DF
215:B3=B:A3=A
300:IF B>1.5LET B=B+.25
301:IF B>1.5GOTO 320
305:IF B>.20LET B=B+.15
306:IF B>.20GOTO 320
310:B=B+.05
320:IF B<4.1GOTO 21
370:LPRINT USING "###.###";"A =";A3
371:LPRINT "B =";B3:COLOR 3
372:LPRINT " ":LPRINT "DA =";J
373:LPRINT "    "
374:LPRINT "    "
375:LPRINT "    "
380:END
600:M=1:X=B
625:IF B<=1GOTO 645
630:M=M*(B-1):B=B-1:GOTO 625
645:G=B+.5772156*(B^2)+(-.655878)*(B^3)+(-.042003)*(B^4)+
    (.1665386)*(B^5)
650:D=(-.0421977)*(B^6)+(-.009622)*(B^7)+(.007219)*(B^8)+
    (-.001165)*(B^9)
655:G=M/(G+D+(-.0002152)*(B^10)):B=X:RETURN
700:X=0:G=0:N=0:R=1
705:GOTO 765
710:N=N+1:R=R*N
765:X=X+(-1)^N*A^N*T^(N/B)/(N/B+1)/R
766:IF X>400GOTO 300
768:IF X<-400GOTO 300
775:D=ABS (X-G)
780:IF  D<0.000001GOTO 790
782:G=X:GOTO 710
790:E=1-(H*T*X):RETURN
```

List 3a.--*Program for FIT-CURVE-A.*

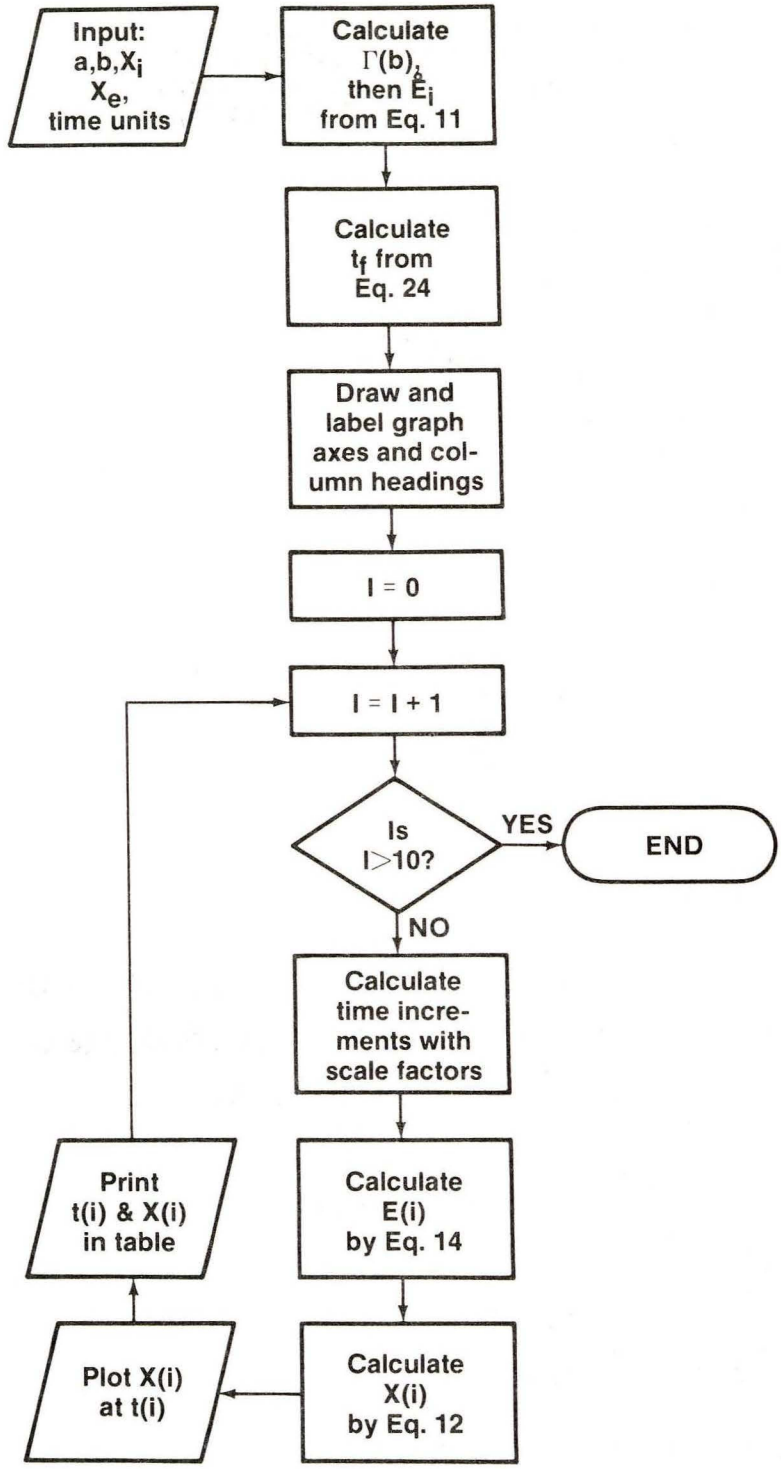

Figure 4a.--*Logic diagram for Program DRY-CURVE-1.*

```
10:INPUT "A=?";A
15:INPUT "B=?";B
16:INPUT "IMC=?";Z
17:S=1.5+2*B
18:INPUT "EMC=";Y
19:INPUT "TIME UNITS=?";A$
20:T=1
22:X=B
25:IF B<=1GOTO 45
30:T=T*(B-1)
35:B=B-1
40:GOTO 25
45:G=B+.5772156*(B^2)+(-.655878)*(B^3)+
     (-.042003)*(B^4)+(.1665386)*(B^5)
50:D=(-.0421977)*(B^6)+(-.009622)*(B^7)+
     (.007219)*(B^8)+(-.001165)*(B^9)
55:H=(-.0002152)*(B^10)
60:G=(G+D+H)/T
70:EO=(1/X)*G*(A^X)
72:B=X
75:F=(S/A)^B
106:G=0
109:H=0
110:GRAPH
125:CSIZE 1
130:COLOR 1
135:LPRINT "          MOISTURE CONTENT, MC"
145:GLCURSOR (30,-34):SORGN
147:FOR I=1TO 4
148:H=H-64
149:GLCURSOR (0,H)
150:LPRINT "-"
152:NEXT I
155:GLCURSOR (-30,-108)
156:ROTATE 1
160:LPRINT "TIME,  ";A$
175:LINE (0,0)-(210,0)
180:LINE (0,0)-(0,-264)
181:LINE (-10,-322)-(210,-322)
182:LINE (160,-360)-(160,-280)
235:GLCURSOR (163,-282)
239:T=0:GOSUB 600
240:LPRINT "T(";A$;")   MC"
241:P=5
242:IF C>25LET P=10
244:IF C>50LET P=20
245:IF C>100LET P=30
246:IF C>150LET P=40
247:IF C>200LET P=50
248:IF C>250LET P=65
249:FOR I=1TO 5
250:G=G+35:D=I*P
255:GLCURSOR (G,29)
260:LPRINT USING "####";D
265:LPRINT " -"
270 NEXT I
275:X=175/C
280:H=26
281:GLCURSOR (-10,5)
282:LPRINT "0"
285:IF F<=2LET MU=0.5
286:IF F<=1LET MU=0.25
290:IF F<=2GOTO 345
295:MU=INT (F/4+1)
345:FOR I=1TO 4
350:H=H-64
355:GLCURSOR (-10,H)
360:LPRINT USING "####.##";MU*I
365:NEXT I
366:GLCURSOR (160,-195)
367:LPRINT USING"###.####";"A =";A
368:GLCURSOR (135,-195)
369:LPRINT "B =";B
370:GLCURSOR (110,-195)
371:LPRINT USING "###.##";"EMC =";Y
374:COLOR 0
375:EA=175*C/(P*5)
380:QA=0
382:H=160:GOTO 401
385:FOR I=1TO 16
387:IF I 4LET I=I+1
390:T=I+MU*.25
391:QB=QA-16
392:IF I>4LET QB=QB-16
394:GOSUB 600
397:EB=C*175/(P*5)
400:LINE (EA,QA)-(EB,QB)
401:H=H-15
403:GLCURSOR (H,-275)
405:LPRINT USING "####.##";T;C
410:IF T=0GOTO 385
411:QA=QB
412:EA=EB
413:GLCURSOR (EB,QB)
414:IF E<.004GOTO 417
415:NEXT I
417:GLCURSOR (0,-485)
418:END
600:TT=0:N=0:R=1:PT=0
607:IF T=0LET E=1.0
608:IF T=0GOTO 717
609:GOTO 665
610:N=N+1:R=R*N
665:S=(((-1)^N)*(A^N)*(T^(N/B)))/
    ((N/B+1)*R)
685:TT=TT+S
690:D=ABS (TT-PT)
695:IF D<0.000001GOTO 715
700:PT=TT:GOTO 610
715:E=1-(EO*T*TT)
717:C=E*(Z-Y)+Y
720:RETURN
```

List 4a.--*Program for DRY-CURVE-1.*

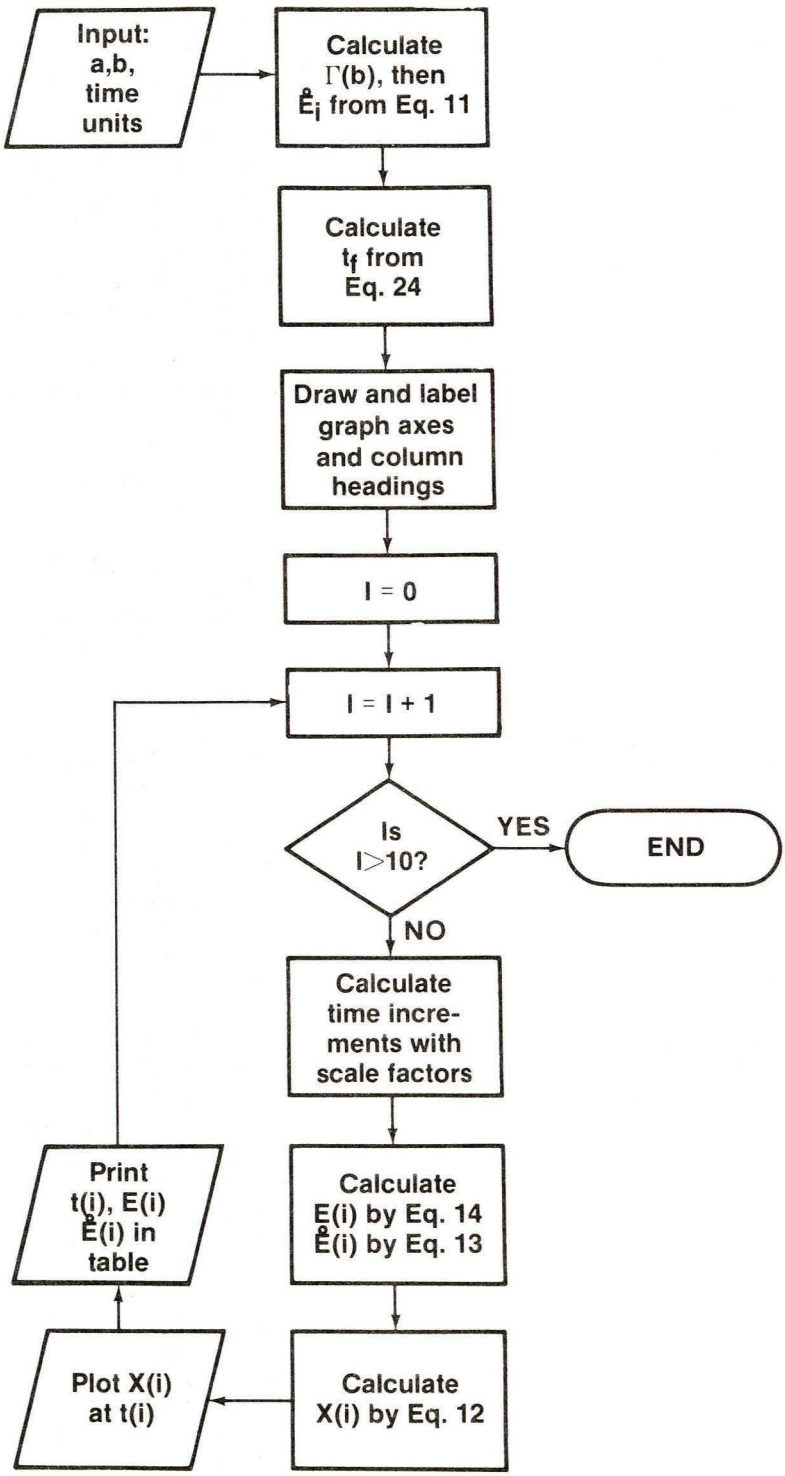

Figure 5a.--*Logic diagram for Program DRY-CURVE-2.*

```
 10:INPUT "A=?";A
 15:INPUT "B=?";B
 17:S=1.5+2*B
 19:INPUT "TIME UNITS=?";A$
 20:T=1
 22:X=B
 25:IF B<=1GOTO 45
 30:T=T*(B-1)
 35:B=B-1
 40:GOTO 25
 45:G=B+.5772156*(B^2)+(-.655878)*(B^3)+
      (-.042003)*(B^4)+(.1665386)*(B^5)
 50:D=(-.0421977)*(B^6)+(-.009622)*(B^7)+
      (.007219)*(B^8)+(-.001165)*(B^9)
 55:H=(-.0002152)*(B^10)
 60:G=(G+D+H)/T
 70:EO=(1/X)*G*(A^X)
 72:B=X
 75:F=(S/A)^B
106:G=0
109:H=0
110:GRAPH
125:CSIZE 1
130:COLOR 1
135:LPRINT "         RELATIVE MOISTURE, E"
145:GLCURSOR (30,-31):SORGN
147:FOR I=1TO 4
148:H=H-64
149:GLCURSOR (0,H)
150:LPRINT "-"
152:NEXT I
155:GLCURSOR (-30,-108)
156:ROTATE 1
160:LPRINT "TIME  ";A$
175:LINE (0,0)-(210,0)
180:LINE (0,0)-(0,-264)
181:LINE (-10,-322)-(210,-322)
182:LINE (160,-400)-(160,-280)
183:LINE (-10,-360)-(210,-360)
235:GLCURSOR (163,-282)
240:LPRINT "T(";A$;")   E    RDR"
245:FOR I=1TO 5
250:G=G+35:D=I*.2
255:GLCURSOR (G,28)
260:LPRINT USING "##.#";D
265:LPRINT " -"
270"NEXT I
280:H=26
281:GLCURSOR (-10,5)
282:LPRINT "0"
285:IF F<=2LET MU=0.5
286:IF F<=1LET MU=0.25
290:IF F<=2GOTO 345
295:MU=INT (F/4+1)
345:FOR I=1TO 4
350:H=H-64
355:GLCURSOR (-10,H)
360:LPRINT USING "####.##";MU*I
365:NEXT I
366:GLCURSOR (160,-195)
367:LPRINT USING"###.####";"A =";A
368:GLCURSOR (125,-195)
369:LPRINT "B =";B
371:COLOR 3
375:EA=175
380:QA=0
382:H=160
383:T=0:GOTO 394
385:FOR I=1TO 16
387:IF I>4LET I=I+1
390:T=I+MU*.25
391:QB=QA-16
392:IF I>4LET QB=QB-16
394:GOSUB 600
396:IF T=0GOTO 401
397:EB=C*175
400:LINE (EA,QA)-(EB,QB)
401:H=H-15
403:GLCURSOR (H,-275)
405:LPRINT USING "####.##";T;E
409:LPRINT USING "###.##^";RR
410:IF T=0GOTO 385
411:QA=QB
412:EA=EB
413:GLCURSOR (EB,QB)
414:IF E<.004GOTO 417
415:NEXT I
417:GLCURSOR (0,-485)
418:END
600:RR=EO*(EXP (-A*T^(1/B)))
605:TT=0:N=0:R=1:PT=0
607:IF T=0LET E=1.0
608:IF T=0GOTO 720
610:GOTO 665
625:N=N+1:R=R*N
665:S=(((-1)^N)*(A^N)*(T^(N/B)))/
    ((N/B+1)*R)
685:TT=TT+S
690:D=ABS (TT-PT)
695:IF D<0.000001GOTO 715
700:PT=TT:GOTO 625
715:E=1-(EO*T*TT)
720:RETURN
```

List 5a.--*Program for DRY-CURVE-2.*

APPENDIX C — EXAMPLE PROBLEM

The drying of ¾-inch-thick pine sapwood at 234°F dry-bulb temperature and 210°F wet-bulb temperature in a laboratory dryer will serve as an example to demonstrate the use of computer package DRYPAC (Kollman and Schneider 1961). First, T_{db} and T_{wb} are input to Program EMC to obtain an X_e of 5.9 percent (fig. 6a). Values of X_i, X_e, X_S, t_S, X_M, t_M, X_L, and t_L are then input to Program FIT-CURVE which converge to a value of a and b in less than 3 minutes with a value of D of only 0.007, indicating a good fit to the three data points. Finally, X_i, X_e, a, and b are input to Program DRY-CURVE-1 for a complete predicted curve, which closely fits all the data points (fig. 6a).

A practical question which can be answered by this example, is "How long would be required to dry this wood to 15 percent moisture content?" From figure 6a, 5.7 hours is necessary.

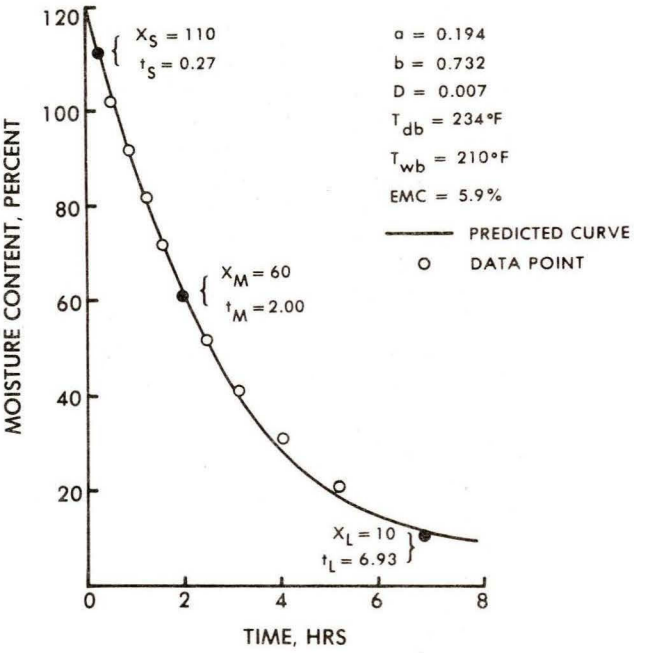

Figure 6a.--*Plot of moisture content versus time for drying pine sapwood (Kollmann and Schneider 1961). The solid line is the predicted curve and the solid circles are the input data points for Program DRY-CURVE-1.*

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Rosen, Howard N.; Martin, Darrell S.
How to use hand-held computers to evaluate wood drying. Res. Pap. NC-263. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1985. 17 p.

Techniques have been developed to evaluate and generate wood drying curves with hand-held computers (3-5K memory). Predictions of time to dry to a specific moisture content, drying rates, and other characteristics of wood drying curves can be made. The paper describes the development of programs and illustrates their use.

KEY WORDS: Drying rate, numerical analysis, models, psychrometric relationships, moisture content.